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Review

Energy critical infrastructures at risk from climate change: A state of the art review

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ABSTRACT

Critical Infrastructure Protection is a relatively new scientific domain stemming from an American Presidential directive PDD-63 of May 1998. Critical Infrastructure (CI) performance and protection are national priorities for all European Union (EU) countries following the introduction of the EU Directive 2008/114/EC, which takes an all hazards approach. This paper has an international focus. At the global and European level, the interest in identifying the impacts of climate change on CIs and extreme weather events (EWE) has increased in the last decades, following several high-profile so-called natural disasters. Concern is evidenced by the UN Sendai Framework for Disaster Risk Reduction and the EU Commission's Staff Working Document on Risk Assessment and Mapping; Guidelines for Disaster Management, SEC (2010) 1626. This paper presents and discusses scientific work which has been published in this area, with a focus on energy CI. The impacts of climate change and extreme weather events on energy CI are initially identified. Important aspects in CI protection such as risk assessment, interdependencies with other sectors, and adaptation/resilience options are subsequently presented and discussed.

1. Introduction

Changing environmental conditions, such as global climate change, affect living species in a variety of ways. One is through extreme weather conditions like heat waves and floods that have become more frequent (Taylor, 2016). Climate change has as well been implicated in extreme weather events such as the 2003 European heat wave; the Pakistan floods and Russian heat wave in 2010; the recent floods in Europe and the drought in California (Mann et al., 2017). During the last decade alone, the increasing number of natural disasters have affected millions of people across the world (European Climate Adaptation Platform, 2016). Due to the social, technological and environmental interconnectedness of modern societies the impacts created by the changing climate can propagate and create cascading stresses (IPCC, 2012).

Energy infrastructures such as, production and distribution systems, are an area of the built environment vulnerable to extreme weather conditions and natural disasters. Such infrastructures are called critical infrastructures (an umbrella term that also includes transportation, Information and Communication Technologies (ICT), water and emergency sectors amongst others) as they are essential for vital societal functions, including the health, safety, security, economic and social well-being of people (Directive 2008/114/EC). History has shown that Energy Critical Infrastructure (ECI) systems can and do fail due to natural disasters or accidental failures with highly consequential impacts to society and the economy (Kyriakides and Polycarpou, 2015). Well-publicized examples include the heatwave in 2003 in Europe, which caused the blackout of many nuclear plants, Hurricane Katrina in 2005, which damaged almost 20% of the U.S. refining capacity, and the persistent extreme cold weather in Alaska, which has stopped the oil flow of the Trans-Alaska pipeline system many times during the last 10 years (Sarafoglou et al., 2013). Modern infrastructures operate as a 'system of systems' with many interactions, interconnections and interdependencies among these systems. Thus, damage in one infrastructure system can cascade and result in failures and cascading effects onto all related and dependent infrastructures eventually impacting the community and the broader economy (European Climate Adaptation Platform, 2016). Such interconnections can be physical, geographical, cyber or logical (Rinaldi et al., 2001). Addressing and preparing for the challenges to critical infrastructure posed by extreme weather events (EWE) is a priority for EU countries as reflected by the EU Directive 2008/114/EC and the EU Commission's Risk Assessment and Mapping Guidelines for Disaster Management SEC (2010) 1626.

This paper focuses on ECI and specifically infrastructures in the

Abbreviations: CI, critical infrastructure; ECI, Energy Critical Infrastructure; EWE, extreme weather events; GHGs, greenhouse gases; ICT, Information and Communication Technologies

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electricity, oil, gas and renewables sub-sectors. ECIs play a vital role in supporting modern society, and are core to the smooth provision of critical services such as health, water and wastewater, and ICT, among others. (Luiijf et al., 2009). Renewable resources at the time of writing may not be fully considered as 'critical' for most European countries since reliance on them is currently low; however, this is likely to change in the future. Climate change risks such as flooding, reduced water supply and extreme temperatures, as well as more frequent and intense storms, will adversely affect energy critical infrastructures, particularly assets of the energy sector (e.g. power stations, electricity substations) that are located in vulnerable areas.

The aim of this paper is to review the literature on the impacts of climate change and extreme weather events on ECI, climate change risk assessment methodologies, interconnections between and among other sectors and adaptation/resilience options for managing the impacts of climate change on ECI. Sources include journals, articles, reports and methodologies which have been published in the scientific literature during the period from 2001 to 2016; selected on the basis of their relevance to the aims of the paper.

2. Energy critical infrastructures at risk from climate change

To understand the risk that ECI face due to Climate Change (CC), it is important to review and understand the following:

- the impacts that CC may cause to ECI (note that ECIs traditionally confront extreme flooding and wildfire events, which are the sequalae of increased climate change as well);
- risk assessment methodologies used in the determination of CC risks and their associated impacts;
- interconnections with other sectors, which may further magnify CC impacts; and
- adaptation/resilience methods for managing and responding to CC impacts.

All papers and reports relevant to this subject have been reviewed and listed. Information such as author, year of publication, type of paper, the energy sector that the paper is focusing are shown in Table 4. In addition, the table shows the area(s) of focus for each paper: impacts of CC, interconnections, and/or adaptation/resilience.

2.1. Impacts of climate change on energy critical infrastructure

Extreme weather events (EWE) are weather events that are rare for a particular area or season, usually at the extremes of the complete range of weather experienced by an area in the past and include events such as floods, droughts, extreme temperatures and precipitations, storms (National Academies of Sciences, Engineering, and Medicine, 2016; Jenkins et al., 2009). A review of the literature indicates that the energy sector is vulnerable to EWEs, with Table 2 summarising key impacts. Due to changing climate, the frequency and intensity of EWEs have increased over the past decades (IPCC, 2014; National Academies of Sciences, Engineering, and Medicine, 2016; Mann et al., 2017) and a further increase is expected as climate change ramifies. ECI and their assets are expected to be impacted by CC in all the four major stages of the energy supply chain: (1) resource extraction and processing infrastructure, (2) fuel transportation and storage infrastructure, (3) electricity generation infrastructure, and (4) electricity transmission and distribution infrastructure (USGAO, 2014), with infrastructure assets in areas that are exposed to EWEs at particular risk. Table 1 provides an overview of ECI and their assets.

Anthropogenic emissions of greenhouse gases (GHGs) have led to an increase in global mean temperature by 0.87 °C since pre-industrial times (e.g., Met Office UK, 2016). This temperature increase affects ECI in many ways: through warmer and more frequent hot days in summer-peaking regions (Abi-Samra et al., 2010); an increase in tropical nights

Table 1
Overview of ECI and their assets.

ECI subsector	Critical services	Associated assets
Oil and Gas	Extraction/ Production Refining/ Processing Transport Storage Distribution to users	Oil platforms (offshore and onshore); gas platforms (offshore and onshore); oil pipelines (offshore and onshore); gas pipelines (offshore and onshore); oil refineries; oil storage facilities; gas treatment and storage facilities; LNG Terminals (liquification and regasification plants)
Coal	Mining/ Extraction Treatment Transport Storage Distribution to users Gasification Liquefaction	Coal Storage Facilities; Coal Handling and Treatment Plants; Coal Gasification Plants; Coal Liquefaction Plants
Renewables	Generation Transmission Distribution	Wind farms (offshore and onshore); solar photovoltaic (PV) farms; concentrated solar PV farms; hydroelectric dams and plants
Electricity	Generation Co-generation Transmission Distribution	Thermal power plants (e.g. oil, coal and gas-fired plants); substations (transmission and distribution); overhead and underground transmission and distribution lines

(minimum temperature exceeding 20 °C); and water availability along with its temperature. Electricity transmission is less efficient during hot days due to the additional resistance induced (Rademaekers et al., 2011). An increase in tropical nights could mean that ECI equipment cannot cool off sufficiently during the night, leading to service disruption or breakdown of ECI assets (Godden and Kallies, 2012). Increases in water temperature may reduce generation efficiency, while extreme temperature could stress the capacity of generation and grid networks as a result of increases in the cooling demands of end-users (ADB, 2012).

In brief, as CC leads to an increase in atmospheric moisture content, the likelihood of extreme precipitation and the risk of flooding increase (IPCC, 2013), with associated physical impacts on ECI assets such as power plants, transmission and distribution substations, underground cables and gas pipelines (McColl et al., 2012), among other assets and related flows of services and products Fig. 1 provides an overview of river flood hazard in Europe, showing areas that may be inundated by a 100-year flood assuming no (further) flood protection for that event (Alfieri et al., 2014). Extreme precipitation may affect hydropower generation, as most current dams were built without taking into account the possible impacts of CC, consequently reservoir capacities may not be sufficient for frequent extreme precipitation events (Mideksa, 2010).

Ocean thermal expansion and melting land ice have resulted in a rise of global mean sea levels by 0.19 m over the last century (Church et al., 2011; IPCC, 2013) with a doubling of the rate of sea level rise in the last 15 years (USGCRP, n/a). Sea level rise is an additional risk for low-lying power plants, such as thermo-electric plants, which are often sited near coastal water bodies for cooling water, and other electricity infrastructure assets sited near coastal water bodies, increasing the risk of coastal flooding from storm surges (Davis, 2014; ADB, 2012; Nierop, 2014; USGAO, 2014).

The Energy sector is highly dependent on water for cooling purposes. Most of the thermal power plants—coal, natural gas, nuclear, biomass, geothermal, and solar thermal— require water for condensing the steam that drives the turbines. As average global temperatures continue to rise, droughts and reduced water supplies are likely to occur, thereby worsening current water supply conditions (Rübbelke and Vögele, 2013) and leading to service disruptions. This has already been observed: For example, droughts in East Africa have shut down

Fig. 1. European flood hazard map for the 100 year return period (Alfieri et al., 2014).

hydroelectric plants leading to country-wide electricity shortages (Loisulie, 2010). Furthermore, drought, along with rising temperatures, heighten the risk of wildfires limiting the amount of electricity that can be generated and transmitted (USGAO, 2014). Droughts and higher air temperatures also work to make wildfires more intense and longer-lasting. Wildfires have major consequences for the energy sector through direct damage to transmission poles, whilst smoke and particulate matter ionizes the air, creating an electrical path away from transmission lines (Davis, 2014).

Rising temperatures and high humidity along with the deposition of dust on insulators, may increase the risk of failures in the electricity transmission system, resulting in more frequent outage of generating units or transmission lines thereby decreasing the available power (Zachariadis, 2012a).

In Table 2, these papers were reviewed with regards to the impacts of climate change on ECI and an overview is provided for each of the energy sub-sectors with respect to the following climate change projections: temperature increases; droughts or decreases in precipitation; sea level rise; extreme weather events including flooding, storms, and hurricanes. Table 2 suggests that research on the impacts of climate change on the electricity and renewable energy sub-sectors has been carried out to a greater extent. The review indicates that a number of authors have identified temperature increases as an important negative impact on electricity and renewables (Kirshen et al., 2008; Abi-Samra et al., 2010; Mideska and Kallbekken, 2010; Golombek et al., 2012; Schaeffer et al., 2012; ADB, 2012; Shoukri and Zachariades, 2012; DOE, 2013; Mukheibir, 2013; Sieber, 2013; Davis and Clammer, 2014; Cortekar and Groth, 2015). Another significant negative is the occurrence of extreme weather events, which will negatively impact ECI across all energy sub-sectors (Schaeffer et al., 2012; ADB, 2012; Cruz and Krausmann, 2013; DOE, 2013; Mukheibir, 2013; Sieber, 2013; Davis and Clammer, 2014; GAO, 2014).

2.2. Risk assessment

The large number of studies, journals and researchers working in the area of risk assessment partly reflects the different interpretations and concepts for risk and probabilistic risk in particular (Aven, 2012). Risk has a variety of common meanings probability of an undesirable event (e.g. floods), probability of death (individual risk), maximum thinkable loss, etc. (Pate-Cornell, 1996). For Magnuson (1997), risk is: "The possibility of suffering harm or loss or danger," which entails risk acceptability "a multi-dimensional concept, comprising numerically calculated values as well as risk perception and risk communication issues". In such ways, risk assessment takes on qualitative and quantitative form. Qualitative risk assessments are – usually – based on a survey tool for compliance that corresponds to the requirements (minima) of a piece of legislation or a relevant standard. Quantitative risk assessments can be mathematical, probabilistic or stochastic depending on the existing or real-time information that will be fed to the model.

Climate change risks are typically defined as or described in terms of the probability of the occurrence of the extreme event multiplied by the impact this may cause (Kaspersen, in press). As Infrastructure is involved, vulnerability of the infrastructure and exposure to threats/hazards are also a major factor. Risk of climate-related impacts result from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Due to the meteorological influence, an amount of uncertainty, which is also variously defined in the literature (e.g., unknown unknowns), is inherent to climate change (Latif, 2011). Uncertainty in climatic phenomena includes natural fluctuation due to the unpredictability of weather and various induced anthropogenic factors. Table 3 illustrates how different authors perceive risk.

For example, the Jones et al. (2003) risk assessment methodology is based upon selecting a standard value (e.g. temperature, wind) and assessing how changing a particular hazard, according to one or more climate scenarios, changes vulnerability. Wisener et al. (2003), on the other hand, aim to integrate natural disaster risk within a wider societal impact mainframe.

Several types of risk assessment methods are employed globally to identify hazards and evaluate risk in relation to critical infrastructure protection (Giannopoulos et al. 2012, Yusta et al., 2011). Only a few of them, however, focus on natural disasters (Idaho, 2006; Australian Government, 2008). Most quantitative climate change risk assessment methodologies rely on the availability of accessible information and predictions on potential climate change hazards, information usually obtained from General Circulation Models (GCM). These models are regionalised by means of dynamic or statistical downscaling techniques (EU-CIRCLE, 2016).

Historically, the Energy Sector has been proactive in developing and applying vulnerability assessment methodologies tailored to its assets, flows and systems. In the 70′s the US Nuclear Regulatory Commission (NRC) adopted measures to calculate risks in new power plants—a first attempt to introduce a formalized risk assessment methodology in the nuclear energy industry. The European Union put in place SEVESO, a holistic risk management system (Directive 2012/18/EU), which applies to all process industries, including natural gas and oil processing industries. Vulnerability assessments deal mainly with the quantified estimation of damage of each element at risk, using fragility functions. That said, no single vulnerability tool or assessment methodology is universally applicable. Stakeholders use different assessment tools that are developed by professional and trade associations, Federal organisations, government laboratories, and private sector firms, which means: The number of tools in use is large, and the vast majority of significant facilities in the Energy Sector have already undergone assessments using one or more of these tools.

2.3. Interconnections with other sectors

Modern ECIs form part of a network, which is itself interconnected

Table 2
Potential CC impacts on ECI.

Climate projection	Potential impacts	References
Oil and gas		
Temperature Increase (including increasing frequency and intensity of extreme heat)	– In colder climates, thawing permafrost impacts oil & gas extraction activities by reducing the timeframe that oil & gas equipment can be operated – In colder climates, thawing permafrost can damage pipelines as soil subsidence jeopardises structural integrity – A reduction in sea ice due to warming temperatures may allow an increase in offshore oil exploration – Higher temperatures impact on oil refining through a reduction in the performance of steam turbines – High water temperatures may result in exceedance of water discharge temperature limits of oil refinery plants – High temperatures may lead to an expansion of oil and gas pipelines	GAO (2014), Cruz and Krausmann (2013), Sieber (2013) and ADB (2012)
Drought or decrease in precipitation	– Drought and accompanying soil shrinkage can affect oil and gas pipelines – Decreasing water availability will affect drilling, production and refining (as large quantities of water are needed) – The water level of rivers may be reduced affecting the transport by barge of crude oil and petroleum products	Cruz and Krausmann (2013), DOE (2013), ADB (2012) and Schaeffer et al. (2012)
Sea level rise	– Coastal oil and gas platforms are at risk of damage or disruption due to storm surges at higher sea levels – Sea level rise exposes coastal oil refineries and gas processing plants to sea water inundation and shoreline erosion	GAO (2014)
Extreme events including flooding, storms, hurricanes	– Reduction or shutdown of oil and gas production (where storms affect coastal or offshore oil & gas platforms) – Storm surge flooding can affect aboveground fuel storage tanks, e.g. tanks partially filled can drift off of their platforms or become corroded by trapped salt water – Floods can impact underground oil and gas pipelines through soil erosion and exposure of the buried pipelines – Storms can affect marine and riverine transport of oil – Flooding can inundate oil refineries with potential for oil spills – Flooding and concomitant lightning can cause any escaped oil to ignite leading to explosions – Hurricanes can damage the infrastructure of oil refineries	GAO (2014), Cruz and Krausmann (2013), ADB (2012) and Schaeffer et al. (2012)
Renewables		
Temperature Increase (including increasing frequency and intensity of extreme heat)	– Increased temperatures lower power cell efficiency and energy output of solar PV power – Increased temperatures lower capacity of underground conductors of solar PV power plants where high ambient temperature increases soil temperature – Increased temperatures increase evaporative losses in reservoirs affecting the availability of hydropower generation – Increased temperatures affect soil conditions impacting on biofuel productivity – Reduction in snow and ice may result in a reduction in stream flows for hydropower production (hydropower plants in many regions rely on ice and snow melt runoff)	DOE (2013), Mukheibir (2013), ADB (2012), Shoukri and Zachariades (2012), Golombek et al. (2012), Schaeffer et al. (2012) and Mideska and Kallbekken (2010)
Extreme precipitation Increase including snowfall	– Changing annual or seasonal patterns of precipitation can affect river flows and water levels behind dams, impacting hydropower output and generation costs – Snow accumulation on solar PV panel reduces their efficiency – Increased precipitation increases the moisture content of biomass which reduces its energy content	Spalding-Fecher et al. (2016), Mukheibir (2013), ADB (2012) and Vicuña et al. (2011)
Drought or decrease in precipitation	– Droughts can result in siltation of river beds and dams which can reduce reservoir storage capacity affecting hydropower – Decreasing precipitation can reduce the amount of hydropower generation due to decreased water storage in dams and reservoirs – Decreasing water availability reduces the potential generation capacity of concentrated solar power – Decreasing water availability results in a decrease in biomass production for biofuel	Cortekar and Groth (2015), DOE (2013), Mukheibir (2013), ADB (2012) and Schaeffer et al. (2012)
Sea level rise	– Damage to offshore wind farms	ADB (2012)
Extreme events including flooding, storms, hurricanes	– Extreme cold periods can alter wind power output through turbine blade icing – Extreme events can damage the infrastructure of offshore wind farms and make access to them (e.g. for maintenance or repair) difficult – Extreme events such as storms and lightning strikes can damage solar PV systems and concentrated solar power infrastructure	DOE (2013), Mukheibir (2013) and ADB (2012)

(*continued on next page*)

Table 2 (*continued*)

Climate projection	Potential impacts	References
	– Increased risk of physical damage or destruction to hydropower generation infrastructure e.g., from debris such as logs damaging the system	
Electricity		
Temperature Increase (including increasing frequency and intensity of extreme heat)	– Reduces generation efficiency – Reduces the electricity capacity of transmission lines/grids – Increases losses within substations and transformers – Increasing water temperatures can reduce plant generation efficiency and may result in exceedance of thermal discharge limits – Heatwaves can result in the failure of transformers as higher temperatures increase their deterioration	Cortekar and Groth (2015), Davis and Clammer (2014), DOE (2013), Sieber (2013), ADB (2012), Golombek et al. (2012), Schaeffer et al. (2012), Abi-Samra et al. (2010), Mideska and Kallbekken (2010) and Kirshen et al. (2008)
Extreme precipitation Increase including snowfall	– Snow and ice can damage transmission and distribution lines (e.g., through sagging) – Heavy rains and flooding can lead to erosion weakening transmission tower structures	ADB (2012)
Drought or decrease in precipitation	– Drought can increase damage to transmission and distribution lines from increased dust – Water shortages and elevated water temperatures may reduce electricity generation – Decreased soil moisture levels may affect the loadability of underground distribution cables	Davis and Clammer (2014), GAO (2014), ADB (2012), Schaeffer et al. (2012) and Abi-Samra et al. (2010)
Sea level rise	– Increased sea levels and storm surges could damage coastal infrastructure	Davis and Clammer (2014) and ADB (2012)
Extreme events including flooding, storms, hurricanes	– Hurricanes, tornadoes, ice storms, severe lighting, etc. can destroy infrastructure – Flooding can result in soil erosion and physical damage to facilities – Flooding can damage underground cables and infrastructure in general – Flooding and storms can result in inundation of power plant sites – Hurricanes and high wind speeds can damage overhead transmission and distribution lines and can damage or break down cooling towers in power plants – Lightning during a storm can strike tanks in the power plant igniting the fuel – Flooding can result in rupture of underground tanks due to collision with flood debris – Flooding can result in short-circuiting and malfunctioning of cooling systems, safety systems and pumps in power plants	Davis and Clammer (2014) and DOE (2013), Sieber (2013) and ADB (2012)
Wildfires	– Increased risk of physical damage and decreased transmission capacity – Smoke and ash from wildfires can shut down transmission lines causing power outages	Davis and Clammer (2014) and DOE (2013)
Coal		
Temperature Increase (including increasing frequency and intensity of extreme heat)	– In high temperatures or heatwaves coal stocks may spontaneously combust or self-ignite	Sieber (2013)
Extreme precipitation Increase including snowfall	– Increase in the moisture content of coal (wet coal) which reduces its heating value and combustion efficiency	Sieber (2013) and ADB (2012)
Drought or precipitation decrease	– Transport of coal by barge can be affected when water levels in rivers and ports drop too low – Decreased water for mining operations will reduce coal availability and increase the probability of seam fires	GAO (2014)
Extreme events including flooding, storms, hurricanes	– Reduced coal production (if storms affect opencast excavation equipment) – Flooding can affect the quality of coal – Flooding may affect railway lines disrupting coal transportation – Transport of coal by barge can be affected when water levels in rivers and ports are too high, such as during a storm surge drop	GAO (2014), ADB (2012) and Schaeffer et al. (2012)

to other CI networks (e.g. ICT, transport networks.), resulting in modern CI acting as a ‘network of networks’. This interconnectedness results in intraconnections between the CI of the different energy subsectors but also interconnections between ECI and other CIs. Such dependencies (intra and inter) are important as they give rise to cascade effects, whereby a disruption in one CI ‘flows or cascades’ through the originating CI to other CIs, resulting in their disruption. Cascade events thus have the possibility to magnify the effects of a disruptive event, with significant costs.

ECI are integral to other CIs as most need energy, often electricity, to operate. Research has highlighted the importance of ECI to the smooth functioning and operation of CIs in other sectors and has identified ECI as the originator of a number of cascading disruptive events (Lineweber and McNult, 2001; Luiijf et al., 2009; Kjølle et al., 2012; Lauge et al., 2015). Luiijf et al. (2009) report that 60% of all cascading disruptions originate in the energy sector cascades, they are therefore fairly common with clear pathways of spreading. Van Eeten et al. (2011) conclude that 47% of all cascades originate once again within the energy sector. Amin (2002), reports that in strategic sectors such as energy, a development in one part of an infrastructure network

Table 3
Different approaches on assessing risk.

No	Author	Year	RISK =
1	Crichton	1999	hazard × exposure × vulnerability
2	Davidson	1997	hazard × exposure × vulnerability × capacity measures
3	Jones et al.	2003	probability × consequence
4	Villagran de Leon	2004	hazard × vulnerability × deficiency in preparedness
5	Wisener et al. (UNDP)	2003	hazard × vulnerability

can rapidly create much broader effects by cascading throughout the network and possibly spilling over into other networks. Conversely, Kunz et al. (2013) show that there is a strong dependency between power and ICT systems, with ECI strongly reliant on ICT systems to operate.

Identifying and understanding dependencies within ECI and across other CI sectors is vital, particularly in times of disruptive events or crises like EWEs. Hurricane Sandy in 2012 is an example of the impacts of cascading effects as a result of the interconnections across different CIs. Management of interconnections is thus important where it helps protect CI from potential domino or knock-on effects generated by the outage of a critical resource (Robert et al., 2015).

Rehak et al. (2016) distinguish two types of impacts that arise due to CI interdependencies during a disruptive event. One type of impact is internal to the CI system (Rinaldi et al., 2001), e.g. when a disruption in a CI might cause the failure of a component in another CI, which subsequently might affect another CI and so forth resulting in a cascading failure. By way of example, following a flood, natural gas infrastructure might be affected and this might result in a failure of an electric utility's generating unit located in the service territory of the gas system which might cause a shortage of generation in the area. A lack of electric power may further affect other infrastructures serviced by the utility. The second type of impact identified by Rehak et al. (2016) is the impact external to the CI system, and affects society (European Council, 2008), in a larger scale, possibly creating economic, societal or political disruption.

Table 4 indicates that there is only a very small number of scientific articles that cover interconnections between CIs (26 over 82 papers). More general, authors have studied interconnections but, as they are not referring specifically to the energy sector, they were excluded from our sample.

2.4. Adaptation/resilience

Our review of the literature indicates that the potential impacts of climate change to ECI (Table 2) are numerous, and in many cases, may interact and compound each other during EWEs. When ECI are damaged or fail due to EWEs, the smooth functioning of society is disrupted, with negative impacts on communities' well-being, severe economic losses and interruption of many critical services (NIST vol 1). Yet, as the US National Infrastructure Advisory Council states '…[w]e cannot reroute hurricanes… or prevent every disruption' to infrastructures. It is difficult to protect all ECI assets at all times, e.g., to guard all electricity transmission networks. This has led to the wide recognition in recent years for the need for resilience—the capacity of a system to function in the face of disturbance (Holling, 1973; Rockefeller Foundation and Arup, 2014)–by a number of different organizations and publications [for example, (ICE, 2009; European Commission, 2009; DHS, 2013, the Hyogo Framework for Action 2005–2015 and the Sendai Framework for Disaster Risk Reduction 2015–2030].

When it comes to analysing the potential impacts of CC on the ECI, we must recognize that many definitions of resilience exist and are pertinent to our subject area (Carpenter et al., 2001; Bruneau et al., 2003; McDaniels et al., 2008; McBain et al., 2010; Hallet, 2013; Turnquist and Vugrin, 2013):

- Prevention or anticipative capacity i.e. preparedness and planning to reduce the impact of a disruptive event, e.g., through plans and programmes to ensure continuity of operations;
- Robustness or absorptive capacity, i.e. the ability to withstand or absorb the impact of a disruptive event with minimal interruption through redundancy and/or substitution;
- Ability to rapidly recover from a disruptive event i.e. through well-trained, experienced and resourceful operators and staff which can manage in real-time the resilience of operations; and
- Adaptive capacity, the ability to learn, re-organise and improve from a disruptive event.

One factor in ensuring the future climate resilience of ECI is the reduction of their exposure to hazards/threats and thus their vulnerability–to climate-related risks. Existing ECI have been designed and constructed in accordance to national building codes and infrastructure standards (Auld and Maclver, 2006; Connor et al., 2013) which set out climatic design values that aim to build resilience to climate in infrastructures (Ruth and Coelho, 2007; Auld, 2008; Connor et al., 2013) through increasing their robustness and absorptive capacity. Types of climatic conditions for which infrastructure standards provide design parameters are: wind, rain intensity, water level, waves, cold and hot temperatures, humidity, and calculated return periods for extreme weather.

Climatic design values are, however, calculated using historical climate data and trends, under the assumption that the average and extreme weather conditions of the past represent climatic conditions over the lifetime of ECI (Ruth and Coelho, 2007; Auld, 2008, Connor et al., 2013; Auld and Maclver, 2005; Auld and Maclver, 2006; Infrastructure Canada, 2006; Means et al., 2010). Existing ECI have thus been designed using climatic design values which assume that climate exhibits stationarity and stationary return levels, i.e., little or no change to the frequency of EWEs over time (Means et al., 2010). Nevertheless, climate change predictions indicate that future climate will not be consistent with that of the past, with an increase in the frequency of climate extremes likely to continue and change into the future (IPCC, 2014). ECI therefore may not be resilient to these continued and expected increases in the magnitude and frequency of extreme weather events (USGAO, 2014).

Planning for climate change resilience, in other words, requires further understanding of how climate change will impact ECI, how these impacts on ECI can affect other CIs (with an impact on the overall resilience of CI networks), as well as how impacts of climate change on other CIs could affect ECI (Scalingi and Folga 2013; NIST Vol 2, 2015; NIST Brief Guide, 2016). This is an especially complex task and is made all the more urgent by the fact that the majority of the studies reviewed fail to consider time–dependent behaviour of CI interconnections i.e. how these interconnections and the cascading effects behave over time (Lauge et al., 2015). In this respect, it is difficult not to conclude that priorities place on joint emergency preparation, training and exercises involving interconnected CI go some way to improving resilience.

Practical resilience and adaptation measures for ECI seeking to address climate change impacts and uncertainties constitute a relatively new field of study, as indicated in our review. Only a small number of the publications cover this subject as indicated by 33 papers out of the total reviewed. It is our opinion that ECI Resilience to climate change should be seen as a major component, focus and driver of action within Critical Infrastructure Protection. Our analysis suggests that studies should be further extended on climate change resilience and recovery time from EWEs, taking into account the costs of the different resilience and adaptation options.

Table 4
Overview of research on CC impacts on ECI and adaptation measures.

No	Author	Year of publication	Type	Energy Sector	Impacts of Climate Change	Interconnections	Adaptation Resilience
1	Abi-Samra N.C. et al.	2010	Scientific article	Power systems	x		
2	Alderson et al.	2015	Scientific article	All sectors			x
3	Argonne National Laboratory (part of U.S. Department of Energy)	2017	Report/ methodology	All sectors		X	x
4	Asian Development Bank	2013	Report	All sectors	x		x
5	Asian Development Bank (2)	2012	Report	Electricity	x		x
6	Australian Government	2008	Report/ methodology	All sectors		X	x
7	Robert R. et al.	2015	Scientific article	All sectors		X	
8	Bollinger L.A.	2014	Scientific article	All sectors	x	X	x
9	Chappin E. et al.	2014	Scientific article	All sectors		X	
10	Ciscar et al.	2014	Scientific article	All sectors	x		x
11	Cortekar et al.	2015	Scientific article	Electricity	x		x
12	Cruz A.M. et al.	2013	Scientific article	Oil & gas	x		x
13	Davis M. et al.	2014	Report	Electricity	x		x
14	Dowling P.	2013	Scientific article	Thermal power plants electricity renewables (photovoltaic panels)	x		
15	Fang et al.	2016	Scientific article	All sectors			x
16	Fant C. et al.	2016	Scientific article	Renewables (wind and solar)	x		
17	GAO	2014	Report	All sectors	x		x
18	Garg A. et al.	2015	Scientific article	All sectors	x		
19	Gaudard L. et al.	2013	Scientific article	Renewables (hydropower)	x		
20	Giannakopoulos et al.	2015	Scientific article	Electricity	x		
21	Giannopoulos et al.	2009	Scientific article	All sectors	x		
22	Giordano T.	2012	Scientific article	All sectors			x
23	Goldman S. et al.	2012	Report	All sectors	x		x
24	Golombek et al.	2012	Scientific article	Electricity	x		
25	Hofmann M. et al.	2011	Scientific article	All sectors			x
26	Homeland Security	2015	Report	All sectors		x	x
27	Hunt A. et al.	2011	Scientific article	All sectors	x		x
28	Idaho National Laboratory (supported by the U.S. Department of Energy)	2006	Report/ methodology	All sectors		x	x
29	Johansson J.	2010	Scientific article	All sectors		x	
30	Jollands N. et al.	2005	Report	All sectors		x	
31	Kadri et al.	2014	Scientific article	All sectors		x	
32	Kopytko N.	2011	Scientific article	Nuclear power	x		x
33	Kirshen P. et al.	2008	Scientific article	All sectors	x	x	x
34	Labriet M. et al.	2015	Scientific article	All sectors	x		
35	Lauge et al.	2015	Scientific article	All sectors		x	
36	Lelieveld J.	2012	Scientific article	Electricity fossil fuels	x		
37	Liu X. et al.	2012	Scientific article	Natural gas	x		
38	Los Alamos National Laboratory (operated by University of California)	2005	Report/ methodology	All sectors		x	
39	Luiijf E. et al.	2009	Scientific article	All sectors		x	
40	Madani K.	2014	Scientific article	Renewables (hydroelectricity)	x		
41	Madani K. et al.	2010	Scientific article	Renewables (hydropower)	x		
42	Maran S.	2014	Scientific article	Renewables (hydropower)	x		
43	McGee S. et al.	2014	Scientific article	All sectors		x	
44	Mideksa et al.	2010	Scientific article	Electricity	x		
45	Miles E.L.	2010	Scientific article	Electricity renewables (hydropower)	x		x
46	Mukheibir P.	2013	Scientific article	Renewables (hydropower)	x		x
47	Nierop S.	2014	Scientific article	Electricity	x		x
48	Ouyang	2014	Scientific article	All sectors		x	
49	Panagea I. et al.	2014	Scientific article	Renewables (photovoltaic panels)	x		
50	Pescaroli et al.	2016	Scientific article	All sectors		x	
51	Rinaldi et al.	2001	Scientific article	All sectors		x	
52	Rübbelke and Vögele	2011a	Scientific article	Electricity	x		
53	Rübbelke and Vögele (2)	2011b	Report	Nuclear power	x		
54	Rübbelke and Vögele	2013	Scientific article	Hydropower fossil fuel nuclear power plant thermal power plant	x		
55	Sage et al.	2016	Scientific article	All sectors			x
56	Sandia National Laboratories	2008	Report/ methodology	All sectors		x	
57	Schaeffer et al.	2012	Scientific article	Electricity	x		
58	Shen S. et al.	2016	Scientific article	All sectors	x		x
59	Shoukri E.	2012	Scientific article	All sectors	x		x
60	Sieber J.	2013	Scientific article	Thermal power plants	x		x
61	SINTEF	2008	Report/ methodology	All sectors		x	x
62	Spalding-Fecher R. et al.	2014	Scientific article	Renewables (hydropower)	x		
63	Stadler S. et al.	2015	Scientific article	Renewables (wind power)	x		

(continued on next page)

Table 4 (*continued*)

No	Author	Year of publication	Type	Energy Sector	Impacts of Climate Change	Interconnections	Adaptation Resilience
64	Stelzer V. et al.	2014	book (section 5)	Thermal power renewables (hydropower)	x		x
65	Stergiopoulos et al.	2015	Scientific article	All sectors		x	
66	The Federal Government	2008	Report	All sectors	x		x
67	Taylor I.	2016	book chapter	All sectors		x	
68	Tobin I.	2015	Scientific article	Renewables (wind power)	x		
69	Utne I.B.	2011	Scientific article	All sectors		x	
70	U.S. Department of Energy	2013	Report	All sectors	x		x
71	U.S. Government Accountability Office (USGAO)	2014	Report	All sectors	x		x
72	Van Eeten et al.	2011	Scientific article	All sectors		x	
73	Vicuña et al.	2011	Scientific article	Renewables (hydropower)	x		
74	Vicuña et al. (2)	2008	Scientific article	Renewables (hydropower)	x		
75	Vicuna and Dracup (3)	2007	Scientific article	Renewables (hydropower)	x		
76	Wilbanks T.J.	2014	book (chapter 3)	Oil & gas thermal power renewables	x		
77	Yao et al.	2012	Scientific article	Renewables (wind power)	x		
78	Zachariadis T.	2016	Book	All sectors	x		x
79	Zachariadis T.	2012a	Scientific article	Renewables (hydropower) electricity	x		x
80	Zachariadis T. (b)	2012b	Scientific article	Electricity thermal power renewables (hydropower, solar energy)	x		x
81	Zhang et al.	2011	Scientific article	All sectors		x	
82	Zimmerman R.	2004	Scientific article	All sectors		x	

3. Further results, analysis and discussion

According to Table 4 and Fig. 2, most of the papers (47%) reviewed identify the impacts of CC on ECI; 30% of them discuss adaptation and resilience measures and only 23% discuss interdependencies between other sectors. Only 2 papers have fully covered and combined all these three subjects together.

Following Hurricane Katrina in 2005 a slight increase is observed in the interest in this subject of ECI protection from CC. Following Hurricane Sandy in 2012, the interest in research on the impacts of CC on ECI is at its highest levels. You see this most dramatically in Fig. 3, which covers papers published between the years 2001–2016 on ECI protection from CC. Fig. 3, however, underscores that climate change impacts, interconnections and issues of resilience and adaptation remain high on the research agenda and show no signs of disappearing.

To summarize: This review of the research literature on climate change risks in and to critical infrastructures, particularly those in the Energy Sector, has focused primarily on results from 10+ years of international research. In light of the above findings and the publications reviewed, we propose that a more integrative framework be developed for critical infrastructure protection with respect to climate change. In particular, this framework would be developed to better differentiate and take into account, minimally, those categories exampled and detailed in this paper, namely: impacts of climate change, CI interconnections, risk assessment, along with adaptation and resilience.

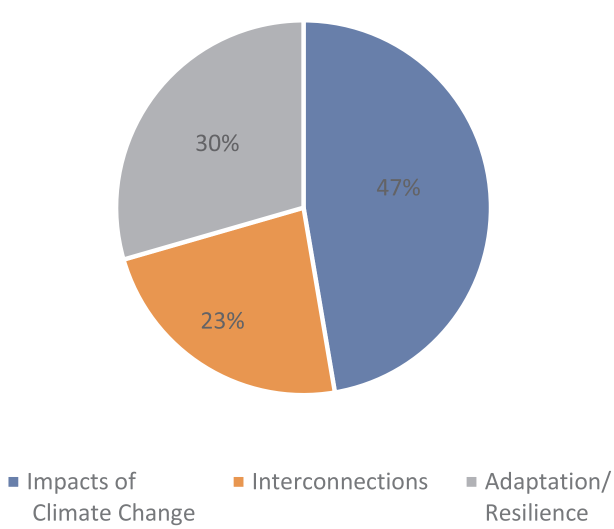

Fig. 2. Breakdown of topics in the papers reviewed.

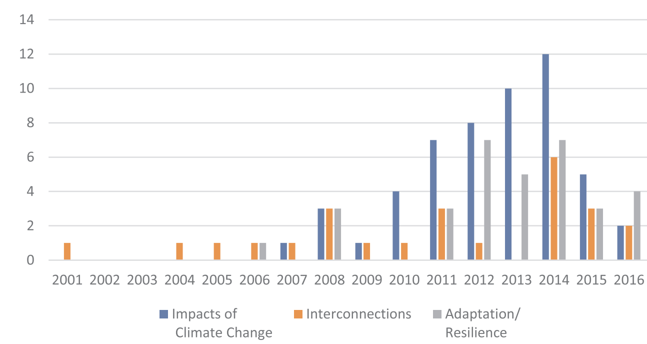

Fig. 3. Chronological increase in research in ECI and CC.

4. Conclusion

The aims of this paper were to identify and discuss the impacts of climate change and extreme weather events on energy CI as well as to present and analyse important aspects in CI protection such as, interdependencies with other sectors, and adaptation/resilience options through the related scientific work that has been published in this area.

The paper surveyed scientific articles and papers that are related to the risks of energy CI regarding climate change and extreme weather events. Specifically, 82 papers have been reviewed and the majority of these choose to focus on impacts from climate change while only a small number of them discuss interdependencies and resilience. Even when studies referred to similar energy sectors and aspects, the respectively analytic and methodological approaches were found to often differ—thus calling for a more integrative approach to the analysis of climate change and ECI along the dimension used in this paper. The urgency in doing so is reinforced by continuing centrality of Energy CI to regions, nations and the global arena.

Unfortunately, meteorological data shows a constant increase of

temperature since the 1950′s in the global stage. This has a number of knock-on effects in various sectors. More work, more papers and more public research funding is needed in order to explore this problem in depth as well as prepare exploratory studies. It is important to take into account the rapid changes of climate and take adaptation and resilience measures now.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ssci.2017.12.022.

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